TEST RESULTS OF THE DOE/SANDIA 17 METER VAWT*

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The DOE/Sandia 17 meter wind turbine began collecting operational data on March 29, 1977. Since then, operation has been conducted on a variety of rotor and drive train configurations. The present log of over 530 hours is an important means of validating theoretical calculations and providing operating experience. This report will contain a brief review of the test program followed by a presentation of the performance results and their significance. Then, in order to provide the reader with an appreciation of the 17 meter operating experience, this report will close with a discussion of the operational difficulties occurring since the first turn 2 years ago.

The 17 Meter Test Program

The characteristics of the 17 meter turbine have been summarized in table I, and the present turbine configuration is illustrated in Fig. 1. Of particular significance is the operation of the turbine in a synchronous mode with the power grid. Control of the turbine is accomplished manually requiring the presence of an operator.

The turbine has been heavily instrumented for data collection. Windspeed is measured by two anemometers situated on a tower 22 feet above the rotor. This measurement may be correlated by recordings at four heights on a nearby tower. The anemometers used are Teledyne Geotech Model 1564B with specified accuracy of ± 1%. Windspeed is corrected to centerline and 30 foot height according to a 0.1 shear factor which has been determined experimentally for the site[1]. The measurement of windspeed is a critical function which has received great attention.

The power train is instrumented at several locations. Rotor aerodynamic power is measured via a precision torque sensor on the low speed shaft. The measurement of this torque sensor is corrected for bearing loss which has been experimentally determined to be 287 ft-lb at standard test conditions. A second torque sensor is mounted on the high speed shaft, permitting transmission loss to be determined. RPM, electrical output voltage, current, and power are measured to complete the power train measurements.

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Stress levels in the system are measured at several points. The brake and transmission temperature are measured. Multiple strain gages generate tower and blade stress information which is pulse code modulated and transmitted to recording instrumentation through a slip ring.

The data collected by these instruments are processed according to the "method of bins"[2]. By this means, average values of power, torque, etc. are calculated as a function of windspeed. This method has been found to yield highly repeatable results for the 17 meter test system; the data presented in this report are based on summing all available data into the calculation.

The various blade and power train configurations which have been tested are shown in table II. The test program has encompassed variations in blade number, blade shape, transmission type, and induction motor size.

Performance Results

Prior to February 1979, testing of the 17 meter turbine was conducted using 21 inch, NACA 0012 blades combined with support struts. The performance testing of these blades has been documented[3]. In March of 1979, testing commenced using 24 inch, NACA 0015 blades without the use of struts. Several preliminary results for the new blades will be presented and compared to the old blades. The results reflect the air density in Albuquerque of .0625 lbm/ft^3 and have not been corrected for sea level.

Selected test results are shown in Figs. 3 to 8. Special attention should be directed to Fig. 8. These preliminary results for the new blade indicate an improvement in performance beyond expectation. Whereas the former strutted configuration performed below analytic prediction, the present unstrutted configuration is exceeding forecast efficiencies over portions of the windspeed range. The observed efficiencies are very favorable.

Analytic calculations in the past have indicated that Darrieus turbines such as the 17 meter test turbine are inherently less efficient than horizontal wind turbines. However, a peak efficiency of 40.9% has been measured which is believed to be comparable to any horizontal axis experience to date. It is hoped that future experimental data will help to clarify the relative efficiency of the Darrieus concept.

17 Meter Test Turbine Encounters with Problems

The inclusion of operating difficulties in this report has not been motivated by the existence of large problems. On the contrary, it is hoped that inclusion will serve to highlight an unusually favorable record for a new concept prototype. The test program to date has not uncovered a single problem likely to affect the economic viability of the Darrieus turbine. Most of the problems involve test instrumentation

not pertinent to normal machine operation. Of the remainder, it is believed that by identifying potential pitfalls here, future designers may be able to avoid them. The difficulties which have been experienced are shown in Fig. 9.

The first problem discovered during testing was an inherent high power loss in the transmission reaching 30 kW. This condition also aggravated a tendency of the 50 hp induction motor to overload during start up. These problems were addressed by first disassembling and inspecting the transmission. After finding no faults, the wet sump lubrication was replaced with a dry sump system. Following this modification, the transmission efficiency improved dramatically as is shown in Fig. 3. No additional start up problems have arisen. A final modification at this time was to increase the induction motor to 75 hp in order to expand the system generating capability using an induction generator. The rating increase was also expected to complement the start up capability.

Occurring next in chronological order were several faults in the data collection instrumentation which had no bearing on normal machine operation. The pressure transducer used to indicate brake pressure failed and was replaced with no problems since. The Pulse Code Modulator used to transmit multiple strain gage measurements developed a faulty power supply which was replaced and no problems have resulted since. The torque sensor used to measure rotor output suffered water damage and had to be rebuilt. Last, the LED readout of RPM became erratic and was replaced.

The lightning protection system for the 17 meter test system consists of a top mounted mast connected to ground through the four guy cables and through the tower via dedicated slip rings[4]. Only the mechanical system is protected. The turbine has undergone five lightning strikes; only the last strike caused discernable damage. High voltage passed through the anemometer output wires into the computer interface, damaging several circuit boards. Future effort will be aimed at protecting electronic components.

The most recent difficulty to arise has been the loosening of several bolts and drive shaft keys. As a result, regular inspection of bolts and keys is now performed. The keys were only found to be loosening on shafts where the key was the only locking mechanism transmitting torque. These keys are being replaced by clamp-type arrangements. Both of these problems are to some degree associated with the oscillatory output of the turbine which should be reduced on future designs as a result of torque ripple reduction studies[5].

Two final problems are minor but have been consistently bothersome. The blade hinge pins tend to seize to their bushings and complicate the changing of blades. Secondly, the anemometers are extremely subject to damage from hailstorms, ice, and high wind and have required frequent

repair. Several more robust units are being investigated for use in measuring cut-in and cut-out windspeed such as might be done on a commercial design. However, the test program requires the finest and most precise windspeed measurement available and it appears that the current rate of repair may be unavoidable on the 17 meter testing.

To summarize the conclusions of this report, the 17 meter diameter test bed has thus far produced power efficiency and reliability experience favorable to the Darrieus turbine concept. Continued experimental testing is expected to play an important role in future Darrieus turbine development.

References

1. R. E. Akins, "Wind Characteristics at the VAWT Test Facility," Sandia Laboratories Report, SAND78-0760, September 1978.

2. R. E. Akins, "Performance Evaluation of Wind Energy Conversion Systems Using the Method of Bins - Current Status," Sandia Laboratories Report, SAND77-1375, March 1978.

3. M. H. Worstell, "Aerodynamic Performance of the 17 Meter Diameter Darrieus Wind Turbine," Sandia Laboratories Report, SAND78-1737, September 1978.

4. C. W. Dodd, "Lightning Protection for the Vertical Axis Wind Turbine," Sandia Laboratories Report, SAND77-1241, October 1977.

5. R. C. Reuter, M. H. Worstell, "Torque Ripple in a Vertical Axis Wind Turbine," Sandia Laboratories Report, SAND78-0577, April 1978.

DISCUSSION

Q. What are the details of your theoretical prediction? Are you using a steady profile drag coefficient?

A. Vertical axis technology is not mature, and our analytical techniques are in a state of flux. We presently simulate VAWT aerodynamic performance using a multiple stress tube model which has been tailored slightly to match experimental wind tunnel data. It is not the kind of accuracy we have a lot of confidence in. We are developing additional models.

Q. What do you have for profile drag in this prediction?

A. NASA profiles have known values of drag versus angle of attack. We use a multiple stress tube model which uses momentum equations based upon the NACA data and also wind shear assumptions to calculate aerodynamic data for each stream tube element.

The largest errors in the power coefficients have been at high tip speed ratios, which is a relatively lower operation. There is a contract with Jim Strickland at Texas Tech University to develop a two and three-dimensional vortex model. He recently reported that his model corrects the over-predicted performance at high tip speed ratios.

Q. Did you keep track of the amount of energy used in starting this machine as compared to the total output energy?

A. I am not able to answer that question precisely, except I know that it's insignificant. Mr. Ai says it takes 15 seconds to start.

Q. Concerning the use of the method of bins, what is the repeatability, and how do you decide which test runs to throw away and which to keep? Also, how do you select the anemometers or the position of the anemometers in relation to cross-correlation?

A. To my knowledge, no experimental measures have ever been thrown away. They are all averaged equally in making the performance calculations. As for the anemometry, in cases where there is a question about one of the two anemometers shadowing the other, we always use the upstream anemometer.

Q. Could you comment on the relative differences between using filters and averaging techniques such as that used on the Magdalen Island machine? Have you decided which one does better filtering?

A. We have never used filtering as I understand you to mean, that is, measuring steady state turbine response. We select a time interval - I think it's typically half a second - and at every time interval we instantaneously measure all of the performance parameters and store them. Each of these parameters is then accumulated according to wind speed. There is no filtering. In other words, there is no compensation for a frequency response of the turbine. This includes having a poor response to a gust direction change, etc.

Q. The annual COE figures appear surprisingly low in light of the C_p of 0.41. Would the machine perform substantially better on energy capture if it wasn't run at a constant speed, and how much better could it be?

A. The energy calculations that we use in all of our studies are based upon 90 percent availability, which is a randomly selected number. They are also based upon the current model of theoretical efficiency, not upon the most recent experimental data to which you refer. Regarding the improvement with variable speed, we feel that a potential energy improvement is in the order of ten percent for a 15 mile per hour median wind speed environment. In our studies we have so far determined that variable speed costs too much and it's difficult to control as well.

TABLE I. - 17 METER TEST TURBINE SPECIFICATIONS

	Original Spec	Present Spec (If Different)
Rotor Diameter	54.9 ft	
Rotor Height	55.8 ft	
Swept Area	2014 ft^2	
Ground Clearance	16.0 ft	
Overall Height	110 ft	94 ft
Operating Speed	29.8-52.5 rpm	29.8-54.8 rpm
Number of Blades	2 or 3	
Blade Manufacturer	Kaman	Alcoa
Blade Material	Fiberglass/Honeycomb/Aluminum Extrusion	Aluminum Extrusion
Airfoil Section	NACA 0012	NACA 0015
Chord Length	21.0 in	24.0 in
Use of Struts	Yes	No
Blade Length	79 ft	
Blade Shape	Straight-Circular-Straight	
Blade Joints	Pinned	Rigid
Blade Weight (each)	713 lbm	1370 lbm
Strut Weight (per blade)	446 lbm	0 lbm
Speed Increaser	3-Stage Planetary	3-Stage Parallel Shaft
Manufacturer	Crichton	Philadelphia Gear
Speed Increaser Ratio	42.9:1	35.58:1
Belt Drive Ratio to Motor	1.42:1 to 0.8:1	1.7:1 to 0.92:1
Motor/Generator (Induction)	50 hp Squirrel Cage	75 hp Squirrel Cage
(Synchronous)	75 hp	
Brake	Dual Independent 30" Disc	
Brake Torque Capacity	53,000 ft-lb (each)	
Tower OD	20 in	
Tower ID	18 in	
Number of Guy Cables	4	
Cable Angle (to Horizontal)	35°	
Cable Diameter	1 in	
Cable Pretension	12,000-18,000 lb	
Cable Length	129 ft	

TABLE II. - 17 METER TEST CHRONOLOGY

Item	Date
Begin strutted, 2-bladed test	April 1977
Inspect gear box Fit dry sump lubrication Increase motor rating	June and July 1977
Change to strutted, 3-bladed test	December 1977 January 1978
Change to unstrutted 2-bladed test Change gear box	February and March 1979

THE 17-METER TEST TURBINE.

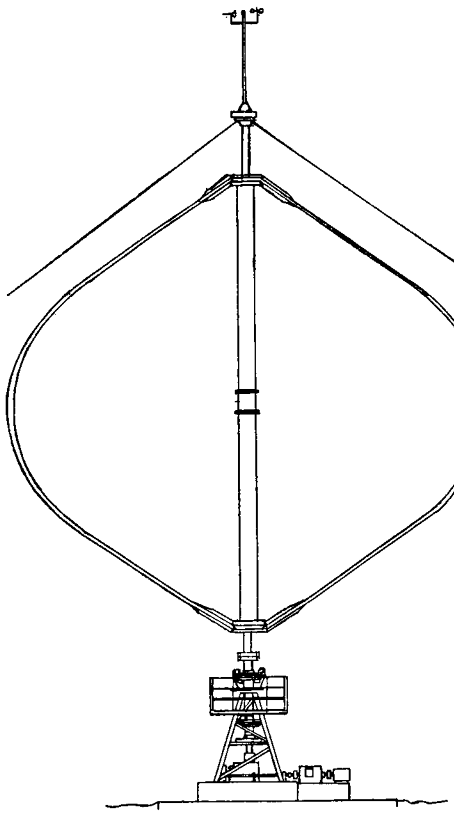

Figure 1.

EFFICIENCY OF THE PLANETARY GEARBOX AFTER DRY SUMP MODIFICATION

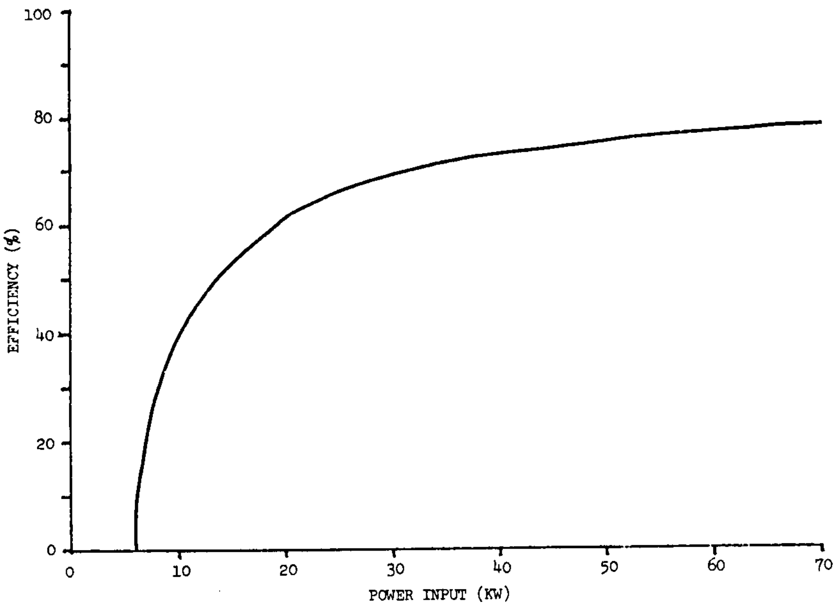

Figure 2.

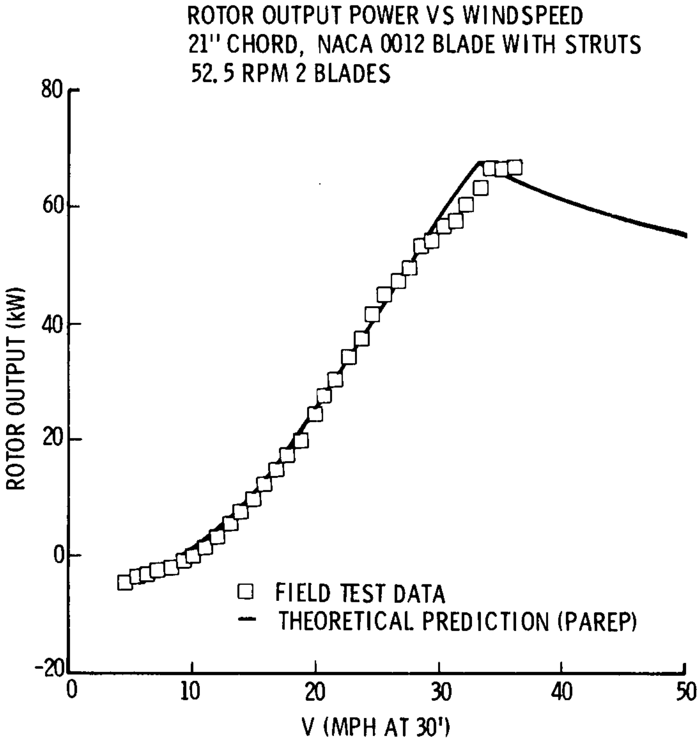

Figure 3.

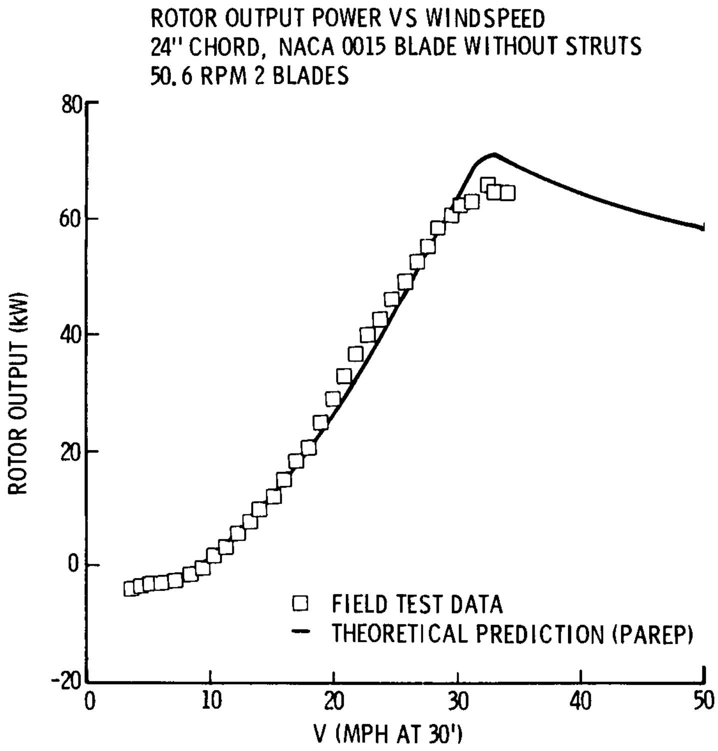

Figure 4.

ROTOR EFFICIENCY VS TIP SPEED RATIO
21" CHORD, NACA 0012 BLADE WITH STRUTS
52.5 RPM 2 BLADES

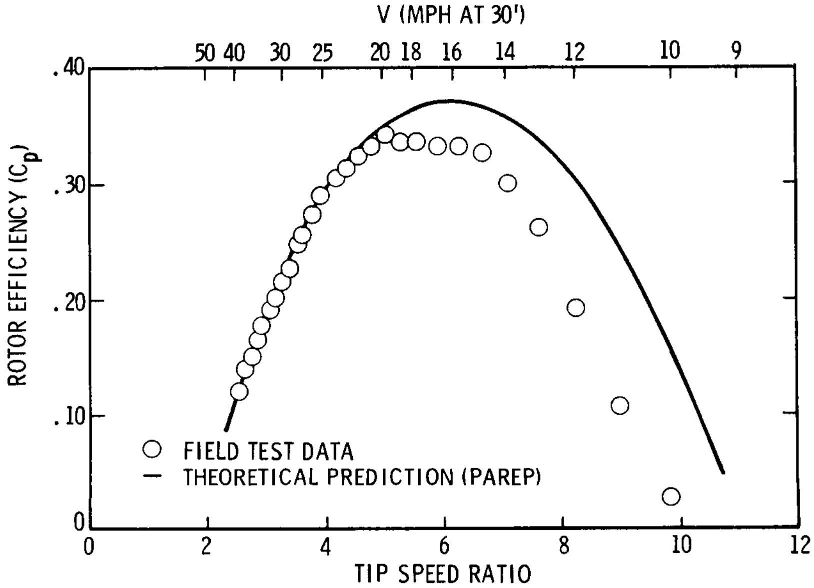

Figure 5.

ROTOR EFFICIENCY VS TIP SPEED RATIO
24" CHORD. NACA 0015 BLADE WITHOUT STRUTS
46.7 RPM

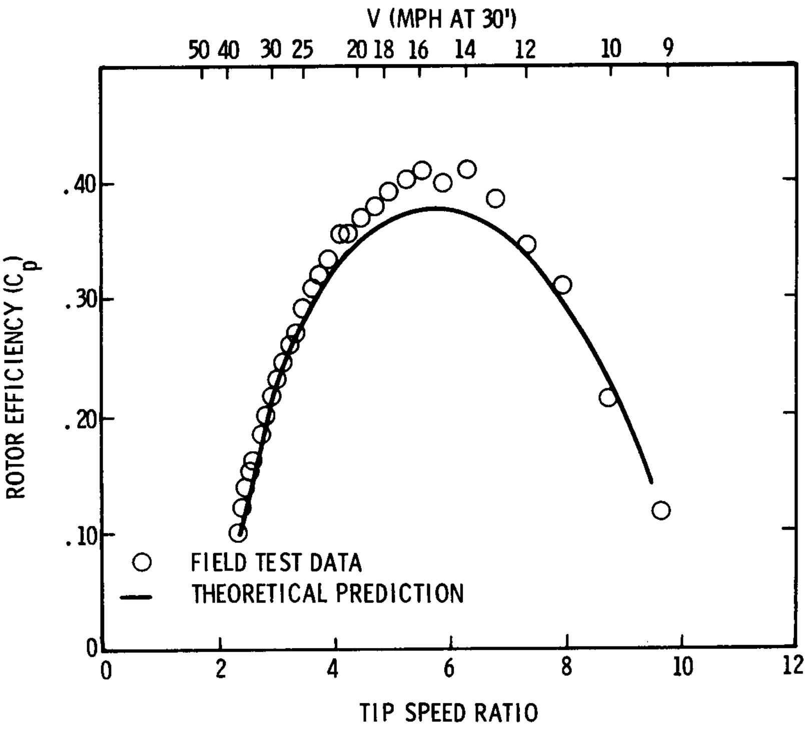

Figure 6.

ROTOR EFFICIENCY VS TIP SPEED RATIO
24" CHORD, NACA 0015 BLADE WITHOUT STRUTS
50.6 RPM 2 BLADES

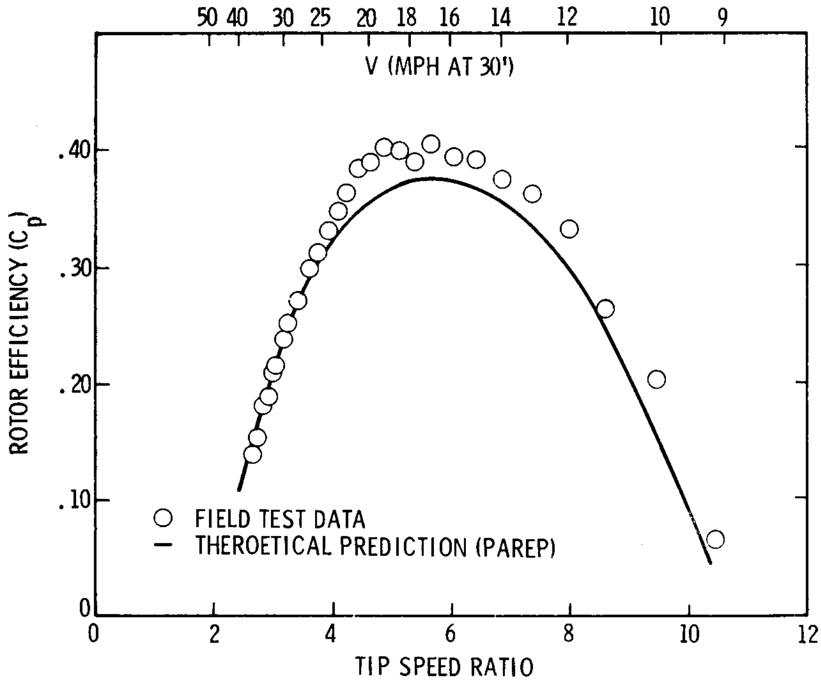

Figure 7.

TWO BLADED ROTOR EFFICIENCY VS TIP SPEED RATIO

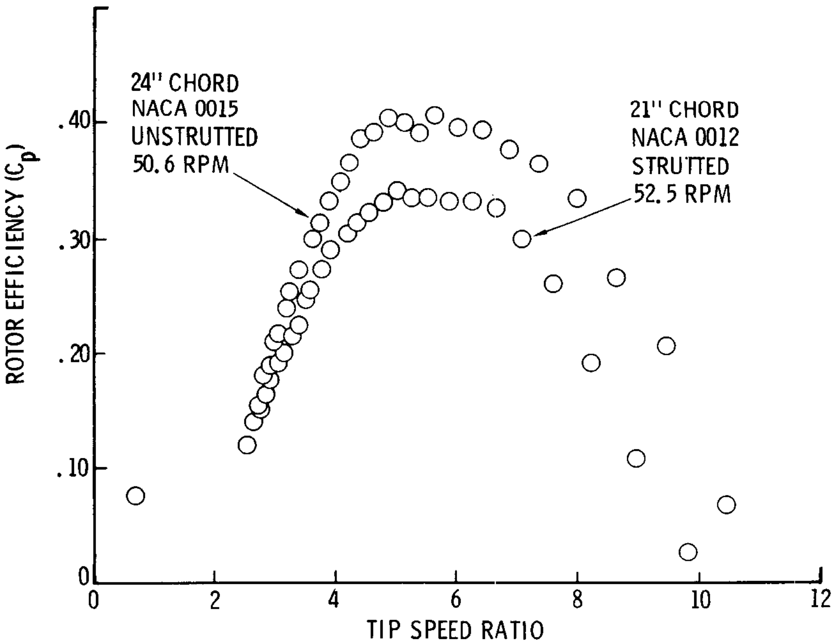

Figure 8.

PROBLEMS ENCOUNTERED IN 17-METER TESTING

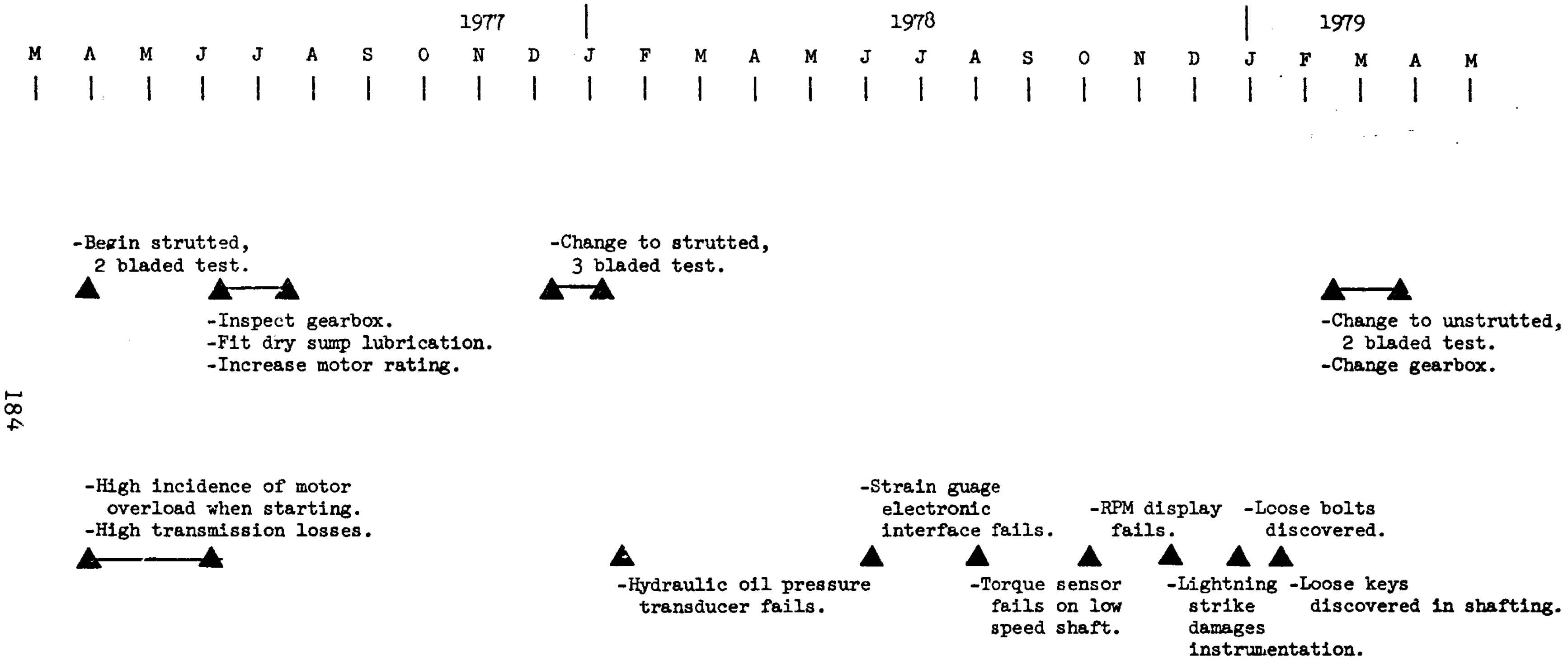

Figure 9